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Cenozoic exhumation patterns in the eastern Sierra Nevada de Santa Marta, northern  
Colombia: A detrital thermochronometry study.

Short version

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## **Abstract**

By capturing the regional signature of source rock exhumation, detrital thermochronology of modern sediments has proven successful in revealing the rates and styles of orogenesis. We applied this technique to a small, high relief mountain range in the Caribbean realm in northern Colombia, the Sierra Nevada de Santa Marta, where the patterns of Cenozoic mountain building remain unclear.

The Santa Marta range is the highest coastal mountain on Earth, with summit elevation in excess of 5.8 km, only 40 km inland to the Caribbean Sea. The age and controlling factors for the formation of such abrupt topography remain loosely understood

New AFT and U-Th/He data from river sand samples of eight catchments draining the eastern flank of the range together with a compilation of published ages, allow us to three exhumation pulses spanning the Cenozoic: An early pulse during the Paleocene-Eocene (60-45 Ma) associated to eastward tilting of the formerly continuous Cordillera Central-Santa Marta range triggered by collision of an oceanic crust along western Colombia; a late Oligocene-Miocene (25-20 Ma) episode of tectonic exhumation associated to opening of the Lower Magdalena Valley, and a late pulse at the middle Miocene (16-10Ma) related to eastward migration of the deformation towards the Cesar Rancheria basins and the Perijá Range, and possibly related to contractional reactivation of the Santa Marta-Bucaramanga fault.

Whilst the Paleocene-Eocene exhumation signature is mainly preserved in the northeastern catchments and the middle Miocene in the southwestern ones, the Oligocene- Miocene is ubiquitous to all them. Three-dimensional thermokinematic modeling calibrated, with available bedrock and our new detrital thermochronometric data document asymmetric exhumation in the Cenozoic with integrated rates of 0.26 km/my in the western margin and below 0.14 km /my to the east. Exhumation rates derived from modeling suggest a post-Miocene acceleration of exhumation.

**Keywords:** Caribbean Plate, asymmetry exhumation, thermokinematic modeling, cooling age peaks.

## Resumo

Ao capturar a assinatura regional da exumação de uma área fonte, a termocronologia de sedimentos detríticos modernos tem se provada bem sucedida para revelar as taxas e estilos da orogênese. Nós aplicamos essa técnica a uma serra pequena de alto relevo na região do Caribe, no norte da Colômbia, denominada Sierra Nevada de Santa Marta, onde os padrões da orogênese no Cenozoico permanecem obscuros.

A serra de Santa Marta é a montanha costeira mais alta da Terra, com elevações superiores a 5,8 km, apenas a 40 km do Mar do Caribe. A idade e os fatores controladores da formação dessa topografia abrupta são vagamente compreendidos.

Novos dados de TFA e U-Th/He obtidas de areia fluvial de oito bacias hidrográficas que drenam o flanco oriental da serra, juntamente com uma compilação das idades publicadas, nos permitem determinar três pulsos de exumação abrangendo o Cenozoico: um pulso precoce durante o Paleoceno-Eoceno (60-45 Ma), associado ao caimento para leste da Cordilheira Central-Serra de Santa Marta, área antigamente adjacente, e que foi desencadeada por colisão de crosta oceânica ao longo do oeste da Colômbia; um episódio tardio no Oligoceno-Mioceno (25-20 Ma) de exumação tectônica associada à abertura do Vale do Baixo Magdalena, e um pulso tardio no Mioceno médio (16-10 Ma) relacionado à migração para leste da deformação em direção às bacias de Cesar Rancheria e a Serra de Perijá, e possivelmente relacionadas à reativação contracional da falha de Santa Marta-Bucaramanga.

Enquanto a assinatura de exumação do Paleoceno-Eoceno é preservada principalmente nas bacias hidrográficas ao nordeste e a assinatura do Mioceno médio no sudoeste, o Oligoceno-Mioceno ocorre de forma generalizada. A modelagem termocinemática tridimensional calibrada com os dados *bedrock* disponíveis e os detríticos obtidos no presente estudo documentam exumação assimétrica com taxas integradas para o Cenozoico de até 0.26 km/My na margem ocidental e menores de 0.14 km/My para o leste. As taxas de exumação derivadas apenas da modelagem de dados sugerem uma aceleração de exumação após o Mioceno.

**Palavras-chave:** Placa do Caribe, exumação assimétrica, modelagem termocinemática, picos de idade de resfriamento.

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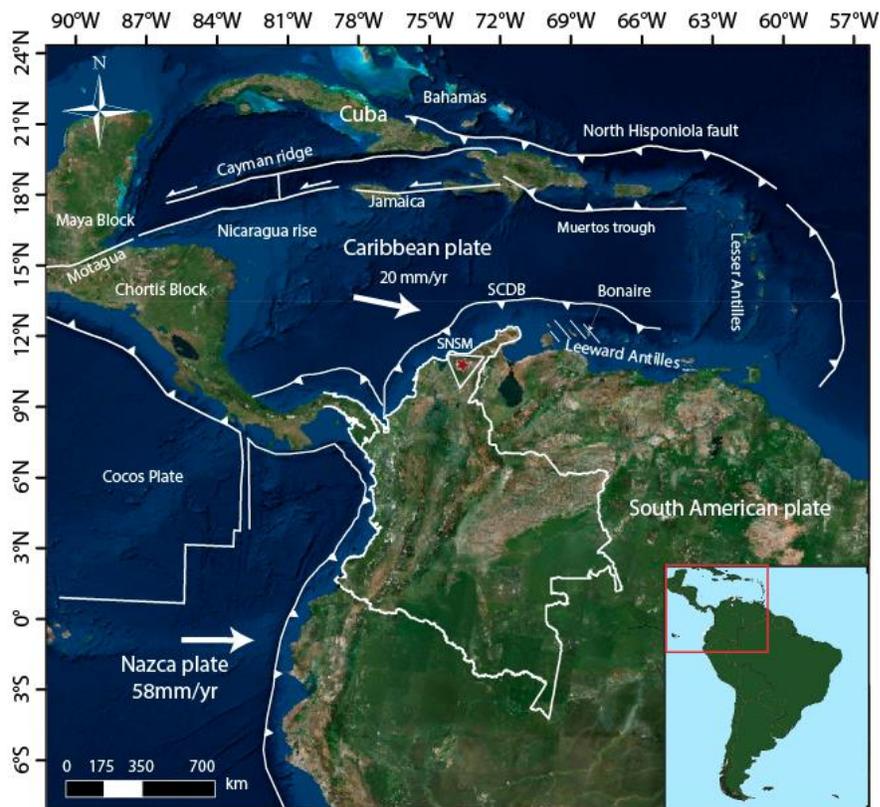
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## 1. Introduction

The rise of mountains is controlled by the competing relation between constructive processes driven by tectonic forces and destructive processes as exhumation and erosion (Reiners and Brandon, 2006). In active convergent margins, the thermal response of the crust during orogeny studied through thermochronological techniques allow understanding aspects as timing and rates of exhumation that ultimately help infer the tectonic mechanism that controls it.

Andean Orogeny in northern South America has been occurring since the Late Cretaceous by collision and subsequent subduction resulting from the convergence between the Caribbean (Pindell and Barrett, 1990; Kerr et al., 1996), and the South American plates (Vallejo et al., 2006; Weber et al., 2009; Bayona et al., 2011; Cardona et al., 2011a).

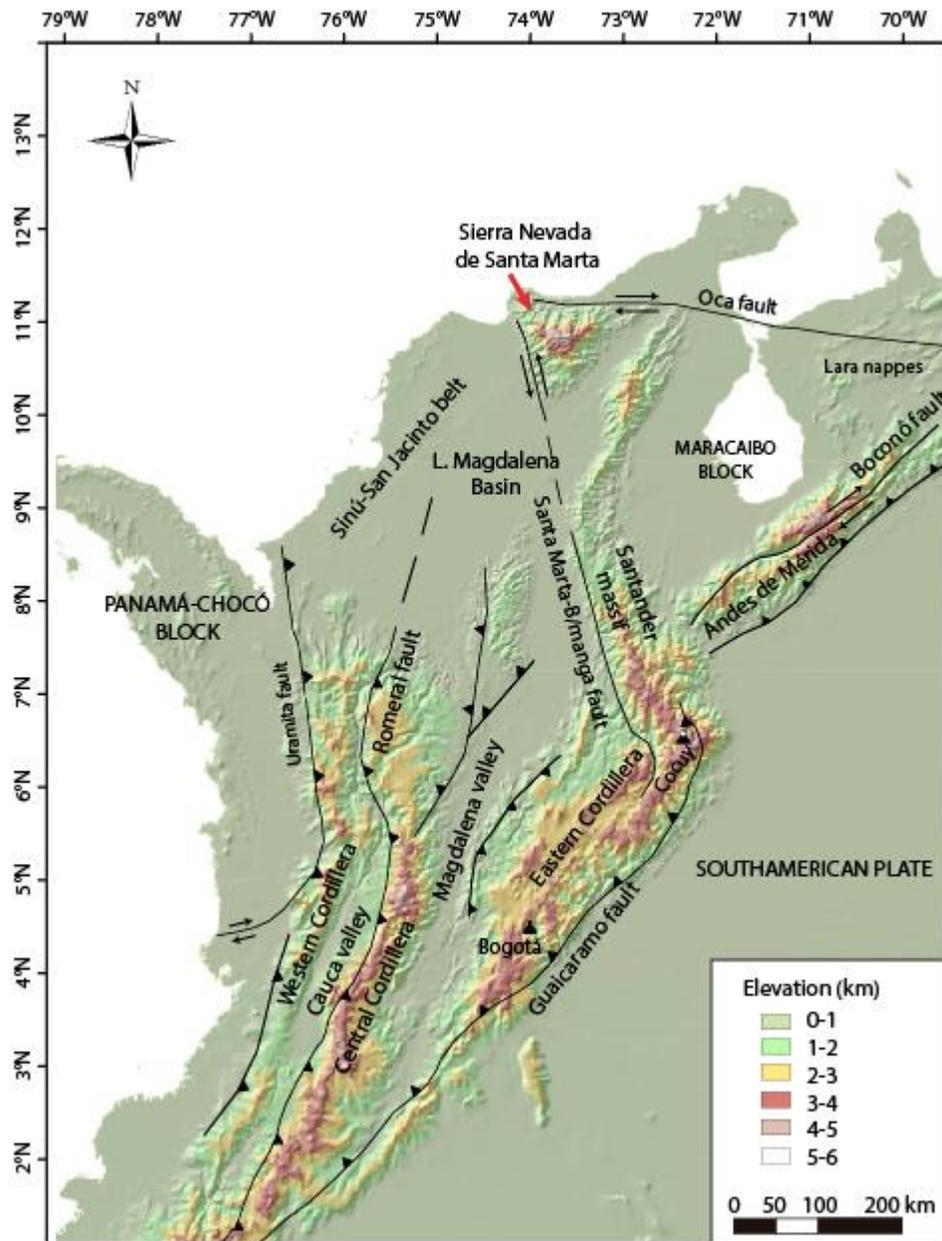


**Figure 1** The present-day tectonic configuration of northern South American plate showing actual convergence rates after Trenkamp et al. (2002). SNSM: Sierra Nevada de Santa Marta, SCDB : South Caribbean deformed belt.

The Caribbean Plate is made up of >15 km of oceanic crust (Bowland and Rosencrantz, 1988) and its origin has been proposed as a Galapagos hotspot that sourced an oceanic plateau and gave rise to a Large Igneous Province with its main magmatic pulse at around 90 Ma (Duncan and Hargraves, 1984; Kerr et al., 1996; Mauffret and Leroy, 1997; Sinton et al., 1998; Thompson et al., 2004). This plate drifted eastward until its present position (Figure 1) (Duncan and Hargraves, 1984; Burke, 1988; Villamil and Pindell, 1998; Kennan and Pindell, 2009), promoting a significant strike-slip regime along its northern and southern plate boundaries (Pennington, 1981; Kafka and Weidner, 1981; Rosencrantz et al., 1988). The northern margin is defined by a left lateral transform boundary along western Guatemala to Lesser Antilles subduction zone. To the western segment, in the Cayman trough more than 1100km of left lateral motion since the Eocene has been documented (Rosencrantz et al., 1988). The southern margin along northwestern South America is defined by a widespread region of oblique and right-lateral deformation (Kafka and Weidner, 1981; Pennington, 1981; Audemard M, 2001). A dextral transpressional regime supports a disassemble of continental fragments subjected to processes of translation and rotation (Montes, et al., 2005a; Montes et al., 2010; Bayona et al., 2010).

The eastward advance of the Caribbean Plate has caused the accretion of Late Cretaceous igneous complexes along the northwestern margin of South America. These units are found juxtaposed to the continental basement through a series of regional fault systems (Kerr and Tarney, 2005; Spikings et al., 2005; Vallejo et al., 2006; Villagómez, et al., 2011a; Weber et al., 2009). Fragments of an intraoceanic arc built over the oceanic plateau are included in the accreted blocks (Burke, 1988; Kerr and Tarney, 2005; Pindell et al., 2005). However, widespread geochronological evidence supports multiple arc systems formed along the eastern margin of the Caribbean Plate (Weber et al., 2009; Bustamante et al., 2011; Wright and Wyld, 2011; Cardona et al., 2012).

The record of oceanic arc-continent collision in the north of Colombia at ca. 70Ma (Cardona et al., 2011a and references therein) include synorogenic sedimentation enhanced by eastward tilting of the continental margin. The provenance signals are interpreted as input of both, Caribbean related and continental uplift blocks that came into being source areas of surrounding foreland basins (Cardona, et al., 2011a; Bayona et al., 2011; Ayala et al., 2012). In addition, a metamorphic event underwent by arc-related lithologies constrained to 65 Ma and a contemporaneous magmatic



**Figure 2.** Main features of the tectonic configuration of the northern Andes (Trenkamp et al., 2002).

peak are associated to this collisional episode (Bustamante et al., 2009; Cardona, et al., 2010a; Weber et al., 2010; Bayona et al., 2012). Subsequent magmatic activity in the continental margin at ca. 54-60 Ma has been related to the subduction of the Caribbean Plate beneath South America (Duque, 2009; Cardona et al., 2011a; Bayona et al., 2012; Salazar et al., 2016).

Evidence for the onset of orogeny includes shortening and early uplift of the Central Cordillera and the development of a foreland basin system, involving the present day Magdalena Valley and the Eastern Cordillera regions (Gómez et al., 2003), documented through rapid cooling episodes in the Central Cordillera (Villagómez and Spikings, 2013; Caballero et al., 2013) and through provenance signals that point out to source of sediment from that range since Maastrichtian (Gómez et al., 2005; Nie et al., 2012; Silva et al., 2013; Horton et al., 2015). Tectonic load exerted by the Central Cordillera influenced the foreland basin modifying the locus of depozones in the sedimentary system. Thermochronological and sedimentary provenance evidence support an eastward migration of deformation during Eocene-early Oligocene whereby contractional deformation was accommodated along inherited Mesozoic extensional structures (Parra et al., 2009; Mora et al., 2010; Parra et al., 2012; Saylor et al., 2012). Such basement anisotropies constitute the main structures through which the Eastern Cordillera uplifted as an inverted bivergent orogen (Mora et al., 2006).

The advance of deformation in the northern Andes has been explained as depicting a non-systematic pattern toward the eastern foreland. This is reflected in a pulse of exhumation at 60-50 Ma found in along the boundary between the Magdalena Valley and the Eastern Cordillera, where Paleogene deposition took place in a wedge top depozone associated to doubly vergent reverse faults (Parra et al., 2012).

The physiography of the Andes in northern of Colombia is characterized by a break in continuity north of  $\sim 7.5^\circ$  N and the presence of isolated fault-bounded blocks, including the prominent Sierra Nevada de Santa Marta. This block is located in the northwestern corner of the major Maracaibo block, which itself is limited to the southeast by the right lateral Boconó fault system, to the west by the left lateral Santa Marta Bucaramanga fault system, and to the north by the right lateral Oca-Ancón fault system (Figure 2) (Taboada and Rivera, 2000; Audemard et al., 2005). The Sierra Nevada de Santa Marta has been interpreted as a crustal block that was attached to the Central Cordillera until pre-late Eocene times (Montes et al., 2010). A connection between them is supported by geochronologic data that allows establishing a correlation among Permo-Triassic rocks found in the basement of the Lower Magdalena basin (Montes et al., 2010; Mora-Bohórquez et al., 2017) and the Santa Marta massif (Cardona et al., 2010b), with the Permo-Triassic basement domain of the Central Cordillera (Vinasco et al., 2006, Villagomez et al., 2011a). Duque-Caro

(1979) and Montes et al. (2010) suggest that this former Permo-Triassic belt was later dislocated to its current northern position by clock-wise rotation.

The disruption of the Santa Marta massif and Central Cordillera has also been explained as a consequence of ~110 km Neogene left-lateral displacement along the Santa Marta – Bucaramanga fault (Campbell, 1965). Recent estimation of low values (3-7Km) of regional shortening in the adjacent Cesar –Rancheria basin based on structural restorations is in agreement with an offset of the Santa Marta massif due activity in the Santa Marta Bucaramanga fault (Sanchez and Mann, 2015). Unlike, higher values (>50Km) are required in the clockwise rotational model that is established considering paleomagnetic data (Montes et al., 2010).

Displacement of crustal blocks results from the oblique convergence and right lateral shearing of the Caribbean and South American plates (Kennan and Pindell, 2009). For instance, right lateral displacement of at least 200 km is proposed for the Island of Bonaire, Leeward Antilles (Figure 1), located to the northeast in the Caribbean plate realm (Zapata et al., 2014). There, Jurassic, Permo-Triassic and Greenville detrital zircon U-Pb age populations in the middle to upper Eocene strata are interpreted as derived from South American massifs and allowed establishing a connection of the island with the northern South American continental margin until the late Eocene (Zapata et al., 2014).

Gravity studies (Case and MacDonald, 1973; Ceron-Abril, 2008; Sanchez and Mann, 2015; Bernal-Olaya et al., 2015; Mora-Bohórquez et al., 2017) detect a positive Bouguer anomaly of above +175 mgal beneath the Sierra Nevada de Santa Marta (Figure 2B). This major anomaly has been associated either with an oceanic crust underthrusting the continent (Ceron-Abril, 2008), or with removal of lower crust leading to recent uplift through northwest vergent overthrusting (Case and MacDonald, 1973).

Such positive anomaly incites a particular interest for the understanding of uplift processes involving the Sierra Nevada de Santa Marta, in the sense of a recent pulse of surface uplift. Other regions with lower but significant topographic elevations show, as is expected, negative gravity anomalies in response to a mass deficit related to the presence of a crustal root reflecting isostatic compensation. For instance, the Bogota high plain (2600 m) , the Cocuy massif (4800) and the

Merida Andes in Venezuela (4200m), correspond to values between -158 to -80mGal (Ceron-Abril, 2008)

Available low thermochronological data from the Santa Marta massif have suggested an asymmetric pattern of uplift (Villagómez et al., 2011b; Piraquive et al., 2017) with an early pulse of exhumation at 60-58 Ma preserved only in the northeastern region of the range and a younger episode of faster exhumation, between 35 and 15 Ma, preserved in the northwestern corner (Villagómez et al., 2011b; Cardona et al., 2011b). Despite contributions of these works, it remains unclear why cooling ages are not so young as it would be expected in a humid region with abrupt topography (60-16 Ma for AFT, 24.6-5.5 Ma for AHe and 26.8 - 18.7 for ZFT ; Villagómez et al., 2011b; Cardona et al., 2011b). For instance, high topography in the Eastern Himalayan syntaxis occurs in an area with high Pliocene exhumation rates  $> 5\text{km/my}$ , in response to a high erosional regime (Lang et al., 2016). Possibly, younger ages in the Santa Marta Massif could remain undiscovered either by insufficient sampling representation or by a still unexposed fossil partial annealing/retention zone, as it is suggested by Villagómez et al. (2011b)

The goal of this study is to document spatial and temporal variations in exhumation rates in the southeastern flank of the Santa Marta Massif and to establish correlations with tectonic episodes involving the Perijá range and the Cesar Rancheria Basin. We employed detrital thermochronology, including apatite fission track (AFT) and (U-Th)/He in apatite (AHe), in modern river sand, in order to take advantage of the wider spectrum of elevations sampled by catchment erosion, and thus, to identify cooling age populations that can be associated to recent exhumation and that allow identifying the controlling factors of such exhumation.

## 2. Regional geological setting

According to GPS velocity vectors, the present-day convergence rates of the Nazca and Caribbean Plates against a fixed South American plate are  $58 \pm 2$  mm/yr in an almost E direction, and 20 mm/yr in an ESE direction, respectively (Figure 1; Trenkamp et al., 2002). These studies also support an NE-directed tectonic scape of the north Andes at a rate of 6 mm/yr (Freymueller et al., 1993; Trenkamp et al., 2002).

Recent plate kinematics in northwestern of South America is dominated by the interaction of the Panamá-Chocó block and the Nazca and Caribbean Plates (Figure 1). The Panamá block is considered as an indenter block undergoing collision with the continental margin of northwestern Colombia at rate of 30 mm/yr (Freymueller et al., 1993; Kellogg et al., 1995; Trenkamp et al., 2002). The subduction of the Nazca Plate beneath the South American Plate at  $5.5^\circ$  N Lat occurs at a dip angle of  $35^\circ$  (Pennington, 1981), bearing an active volcanic arc along the present-day Central Cordillera. Unlike these southern regions of the northern Andes, subduction of Caribbean Plate has a less clear expression due essentially to the lack of well-defined seismic zones and regional earthquakes (Van der Hilst and Mann, 1994; Bernal-Olaya et al., 2015, Mora-Bohórquez et al., 2017).

Active volcanism related to the Nazca Plate subduction is present until  $5.5^\circ$ N; farther to the north, the record is scarce and has been explained as result of the shallow subduction of the Caribbean Plate beneath northwestern Colombia, for instance, (Lara et al., 2013) documented volcanism at 13 Ma in the Sinu belt, and Mantilla-Pimiento et al., (2009) in the Santander Massif at 10Ma. However, Wagner et al. (2017) based on a wide compilation of volcanic ages that postdate the collision of the Panamá-Chocó block (14 Ma, Montes et al., 2015), found a continuous volcanic arc as far to the north as  $7^\circ$ N. Such volcanic activity involving subduction of the Nazca Plate gradually extinguished in response to the development of flat slab subduction between 7 and 2 Ma. Finally, the slab steepened again south of  $5.5^\circ$ N and caused the establishment of the actual volcanic arc.

Geophysical surveys in northern Colombia have been used to suggest a low angle subduction ( $\sim 10^\circ$ , Bernal-Olaya et al., 2015) of the Caribbean Plate beneath South America, which steepens

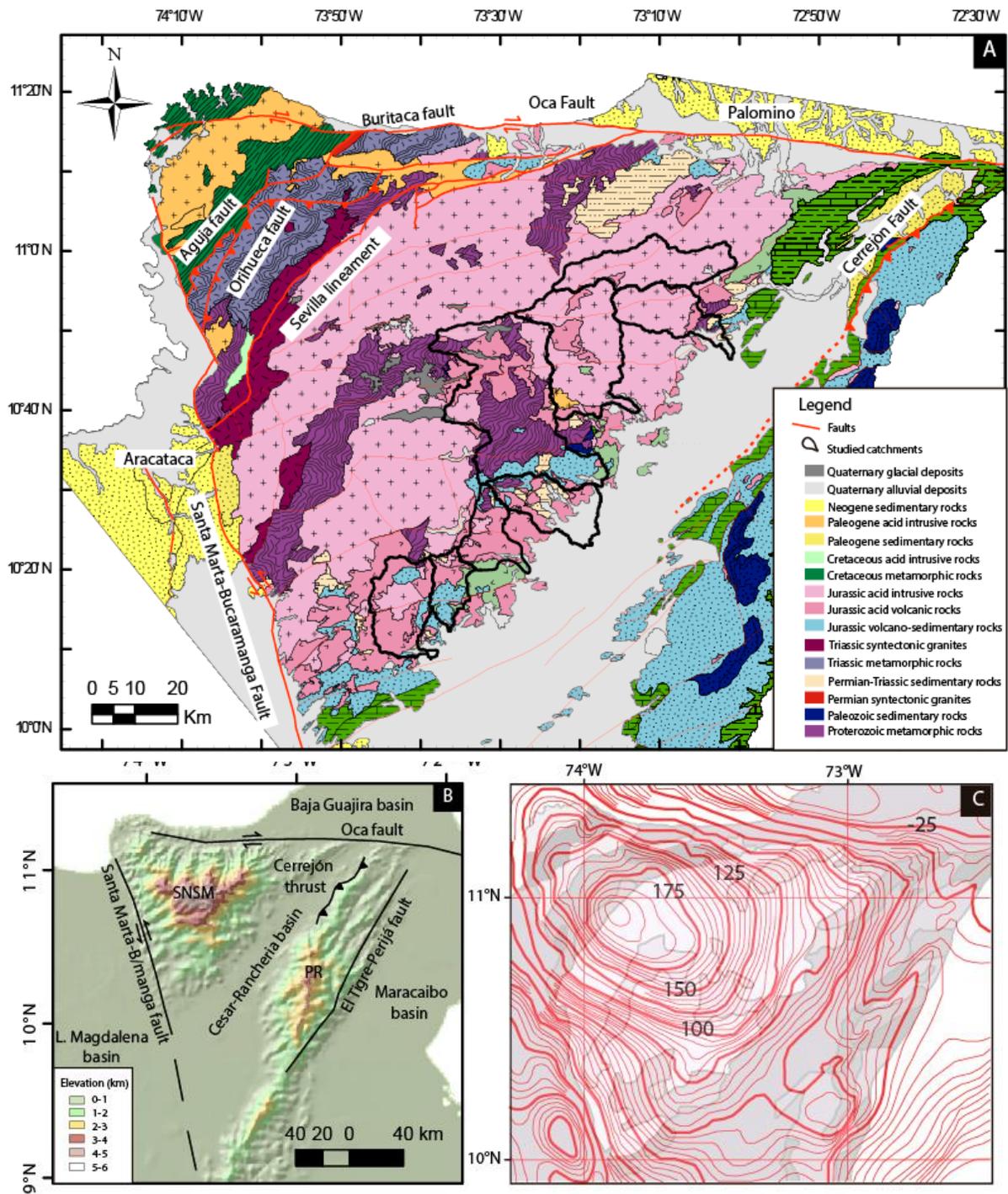
to  $\sim 35^\circ$  at  $\sim 450$  km in a southeast direction from the frontal thrust. Furthermore, according to gravity data, the thickness of the Caribbean slab change from 13-16 km in an offshore region to 7 km in the steeper-dipping part (Bernal-Olaya et al., 2015; Sanchez and Mann, 2015).

### **3. Local geological setting**

The Sierra Nevada de Santa Marta, is a fault-bounded basement uplift with prominent topography, up to 5.7 km at the summits, and a relatively small area of  $\sim 15,600$  km<sup>2</sup>, located above the subducted Caribbean Plate in northern Colombia (Bernal-Olaya et al., 2015). Surrounding the range, to the north of the right-lateral Oca fault lies the Baja Guajira basin and to the southwest of the left lateral Santa Marta Bucaramanga fault the Lower Magdalena basin (Figure 2).

A large vertical component along both faults is inferred by the correspondence between the basement exposure in the Sierra Nevada de Santa Marta and the substrate of surrounding basins (Montes et al., 2010), covered by 8 km of Cenozoic strata in Lower Magdalena (Duque-Caro, 1979) and by 3 km of Meso-Cenozoic strata in Baja Guajira (Rincón et al., 2007).

On the contrary, the range's southeastern boundary against the Cesar-Rancheria basin is in structural continuity with the flank of the range in the form of a monoclinical dipping to southeastern (Tschantz et al., 1969), with a Aptian to recent sedimentary cover of  $>2$  km (Bayona et al., 2007; Ayala-Calvo et al., 2009).



**Figure 3.** Geological map of the Santa Marta massif (Gómez et al., 2015). Black lines denote the limits of river catchments sampled for detrital thermochronometry. B. Main morphotectonic features at the northwestern region of Maracaibo block- SNSM: Sierra Nevada de Santa Marta; SP: Serranía de Perijá. C: Bouguer Gravity anomaly contours (ANH, 2010).

Three major provinces with particular metamorphic basement constitute the Santa Marta massif: (1) the northwest Upper Cretaceous –Paleocene belt of low to middle grade metamorphic rocks; (2) a central province with Paleozoic middle grade metamorphic rocks (3) and a southeastern province conformed by Proterozoic high-grade metamorphic rocks (Tschanz et al.,1974).

The northwest belt is composed mainly by pelitic and psammitic schist and metabasites of greenschist to amphibolite facies formed during late Cretaceous-Paleocene (Tschanz et al., 1974; Cardona et al., 2010a; Zuluaga and Stowell, 2012) , and it is intruded by Paleocene –Eocene rocks with tonalite, quartzdiorite and granodiorite compositions (Duque 2010; Cardona et al., 2011a, Salazar et al., 2016) . The central Paleozoic belt, bounded to the east by the Sevilla lineament and to the west by the Aguja fault, comprises mostly amphibolites, paragneisses and mica schists formed in amphibolite facies (Tschanz et al., 1974; Cardona et al., 2006, Cardona et al., 2010b). This region further to presents Paleocene-Eocene intrusions include Permo-Triassic syntectonic intrusive rocks (Cardona et al., 2010b) .To the southeast, the oldest belt correspond to a Meso-Proterozoic metamorphic basement composed of pelitic, quartz-feldspathic, and mafic gneisses of amphibolite-granulite facies rocks (Tschanz et al., 1974,Cordani et al., 2005;Cardona-Molina et al., 2006).. This province presents undeformed Jurassic intrusive rocks including granodiorites, quartzmonzonites granites and Jurassic-early Cretaceous volcanic felsic rocks (Tschanz et al., 1974). Minor occurrences of Paleozoic and Mesozoic sedimentary and volcano-sedimentary rocks are restricted to this region (Tschanz et al., 1974).

Whereas lithologies of Santa Marta massif are mainly igneous and metamorphic, the Perijá range located to the east and separating the intermontane Cesar-Rancheria basin from the Maracaibo basin to the east (Figure 3B) is constituted mainly by sedimentary sequences with minor exposures of a basement of Precambrian metamorphic rocks (Miller, 1962; Kellogg, 1984).

Stratigraphic correlations of the Perijá range include a Precambrian metamorphic basement overlain by Cambrian-Ordovician, Devonian-Pennsylvanian, Permian and Mesozoic sedimentary sequences with successive unconformable contacts (Tschanz et al., 1974; Miller, 1962). Pre-Cretaceous sequences, lower Cretaceous limestones and an upper interval of Upper Cretaceous and Cenozoic coarse-grained clastic rocks, reach thicknesses about 1000m, 1000m and 5500m, respectively (Duerto et al., 2006). The main tectonic pre-Cenozoic events involving the Perijá range

were a Silurian-Early Devonian orogeny causing weak metamorphism in Cambrian-Ordovician sedimentary rocks, and Jurassic-early Cretaceous rifting and volcanism (Kellogg, 1984).

The Cerrejón southeast dipping thrust marks the eastward boundary of the monocline that defines the structural continuity of the Santa Marta massif and Cesar-Rancheria basin, and the western boundary of the Perijá range (Kellogg, 1984). Its detachment level, as common to several thrusts in the Cesar-Rancheria basin, occurs along incompetent Paleogene strata, (Montes et al., 2010). The Tigre fault along the eastern margin of the Perijá Range has been interpreted either as dextral strike-slip fault (Duerto et al., 2006) or as a north-verging thrust (Kellogg, 1984).

In the Eocene, the Perijá range became a barrier separating the Rancheria basin from the northwestern Maracaibo basin via reactivation of high angle former Mesozoic structures (Ayala et al., 2012). Angular unconformities at 53Ma, 45Ma, and 25Ma along the Perijá range's eastern flank have been interpreted as the consequence of contractional deformation and concurrent uplift of the range. (Kellogg, 1984).

Sedimentation in the Cesar-Rancheria basin since Aptian took place in carbonate platforms above a substratum made of Triassic-Jurassic volcano-clastic and intrusive basement rocks in a passive margin setting controlled by transgressive events (Tschanz et al., 1974; Caceres et al., 1980). Two episodes of eustatic sea-level highs have been recognized, for the Early Aptian and the Cenomanian-Turonian (Martinez and Hernandez, 1992). Depositional environments alternate between inner, middle and outer shelf (Caceres et al., 1980). On the other hand, Cenozoic sedimentation took place simultaneously with contractional tectonic deformation, conforming a synorogenic record (Bayona et al., 2011; Ayala et al., 2012; Cardona et al., 2011a).

Late Paleocene eastward tilting of the crust along a horizontal axis, as proposed by (Montes et al., 2005b), explain coeval uplift of the Sierra Nevada de Santa Marta to the west and concomitant creation of accommodation space to the east, allowing deposition in the Cesar-Rancheria Basin, resulting in an increase of the tectonic subsidence rates, from 48 m/my in early Paleocene to 87m/my in the Late Paleocene.

Provenance signatures such as sandstone composition and detrital zircon U-Pb age document changes in sources of sediments deposited during the Paleogene. Lower to middle Paleocene strata are siliciclastic to the south and carbonate to the north and exhibit predominance of quartz and

sedimentary lithic fragments with a predominance of U-Pb age populations of 0.9 to 2.5 Ga to the north and 1.5 to 2.5 Ga to the south. Such a pattern has been interpreted as the result of the reworking of a Cretaceous cover from sediment sources located to the south, transported along a regional drainage (Ayala et al., 2012).

Coal-rich upper Paleocene strata present an increase of lithic and feldspar components. Their detrital zircon age populations reveal the contribution of Jurassic and Permo-Triassic rocks, and rocks with ages ranging from 65 to 360 Ma, which was interpreted as deposited by a modified drainage system fed by small transversal rivers (Bayona et al., 2011; Ayala et al., 2012; Cardona et al., 2011a). These provenance signals, the preservation of unstable sandstone components probably supplied by a nearby source (Bayona et al., 2007), and high subsidence rates (Bayona et al., 2011), have been used as arguments to propose the Sierra Nevada de Santa Marta - Central Cordillera as source areas (Bayona et al., 2007, 2011; Ayala-Calvo et al., 2009; Ayala et al., 2012; Cardona et al., 2011a).

Overlying the Upper Paleocene sequence, commonly disconformably, (Caceres et al., 1980; Montes et al., 2010; Jaramillo et al., 2010; Bayona et al., 2011), Lower Eocene strata were deposited mainly in fluvial environments. They are characterized by significant changes in composition such as an increase of potassic feldspar, quartz, chert and sedimentary lithic fragments, suggesting the Perijá range as a new source of sediments (Bayona et al., 2011, 2007). Zircon age populations are similar to those of upper Paleocene strata, but, in addition, a new age population of ~50-55 Ma (Bayona et al., 2011; Ayala-Calvo et al., 2009; Ayala et al., 2012; Cardona, 2011a) occurs. This Eocene detrital zircon ages have been interpreted as the result of surface exposure of the Eocene granitoids that intrude the northwestern corner of the Santa Marta Massif (Bayona et al., 2011; Cardona et al., 2011a; Ayala et al., 2012). However, such interpretation is in conflict with geobarometric data of this pluton that reveal a paleodepth of around 15-19 km (4.9—6.4 kbar) during pluton emplacement at 58-60 Ma (Cardona et al., 2011b). Alternatively, interstratification of a felsic tuff ( $56 \pm 0.03$  Ma) reported in lower Eocene strata of northwestern Maracaibo basin (Jaramillo et al., 2010) support coeval volcanism in the area that could source the Eocene zircons.

Post-Eocene sedimentation has been recognized mainly in the subsurface and consists, in the Rancheria sub-basin, to the north, of an Upper Eocene- Oligocene sequence deposited in a tide-influenced platform and unconformably overlain by Upper Miocene fluvial deposits (Caceres et

al., 1980). In the Cesar sub-basin, to the south a continental sequences constituted by sandstones, conglomerates and mudstones likely of a Middle Miocene-Pliocene age have been documented (Geopetrocol, 1998). These sedimentary sequences are characterized by major unconformity contacts at the base and the top.

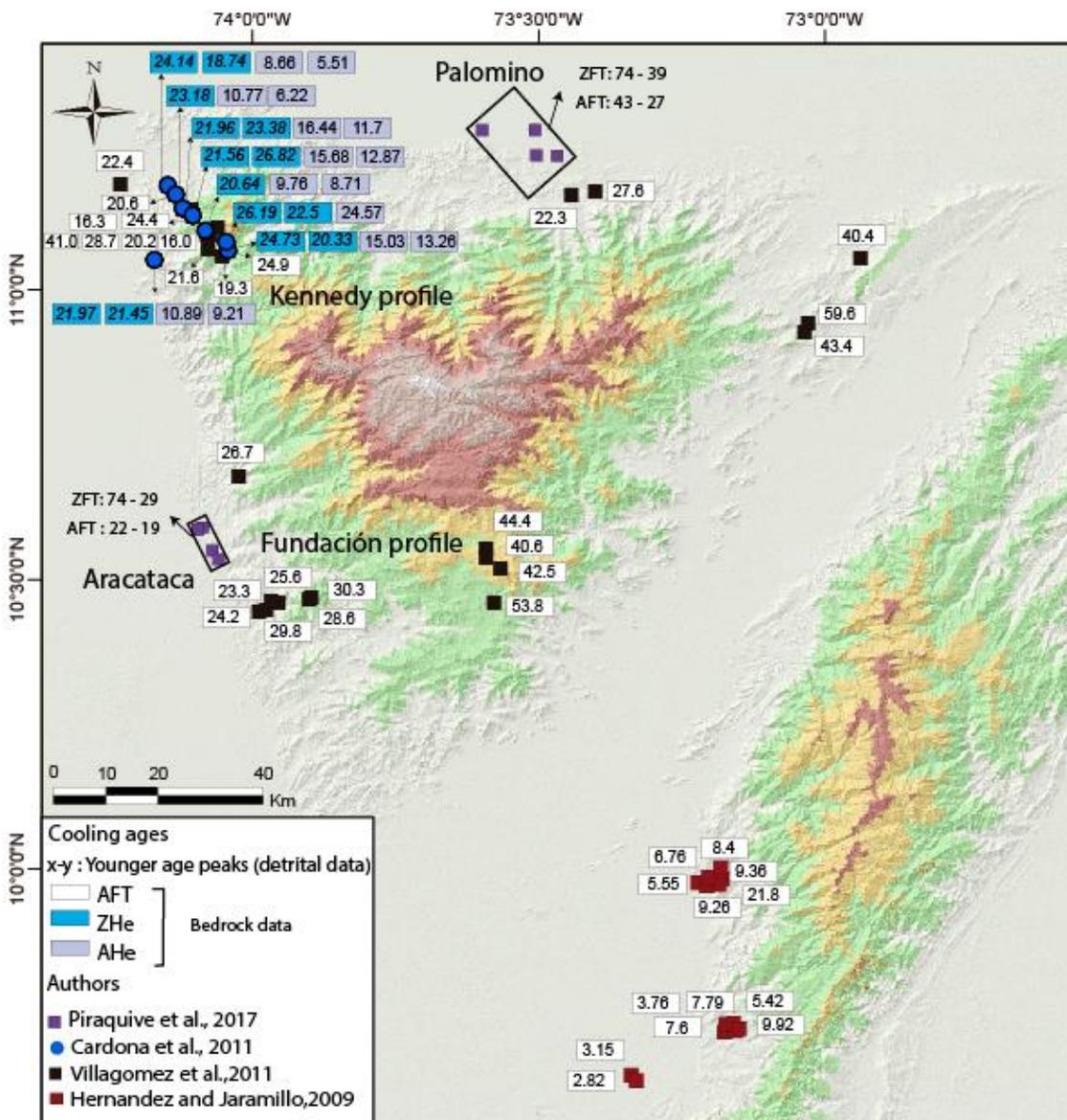
Sub-surface structural mapping in the Cesar-Rancheria basin reveal the presence of a buried fold and thrust belt made of east-dipping reverse faults, the main of which reaches the surface, contributing with the uplift of the Perijá Range (Sanchez and Mann, 2015). Cross-cutting relationships beneath the Miocene-Pliocene unconformity and the preservation of Paleogene units restricted to the easternmost thrust sheets suggest the earlier activity of western faults within the fold-and-thrust belt and supports an eastward advance of the deformational front (Sanchez and Mann, 2015).

Marginal basins located along the foothills of the Santa Marta massif, the Palomino basin to north and the Ariguaní Depression to west, are constituted by similar Neogene sedimentary sequences (Tschanz et al., 1969; Hernandez et al., 2003 ). The Ariguaní Depression comprise a basal sequence of fossiliferous siltstone alternating with marls, sandstone and conglomerates of transitional to shallow marine environments; overlaid by conglomeratic strata of transitional-marine to alluvial environments (Echeverri et al., 2017). To the north, fan delta conglomerates are overlaid by sandstones alternating with siltstones of fluvial and fan delta environments (Echeverri, et al., 2017). Unlike the youngest Paleocene-Eocene detrital zircon U-Pb age populations found in the Paleogene sedimentary units in the Cesar-Rancheria basin, as previously described, the Neogene infill of the Ariguaní and Palomino basins do not contain age populations younger than 116 Ma (Piraquive et al., 2017).

#### **4. Previous thermochronological data.**

Exhumation events during the Cenozoic in the Sierra Nevada de Santa Marta have been recently identified through low-temperature thermochronology suggesting : (1) faster exhumation rates toward northwestern corner (Villagomez et al., 2011b), (2) events of rapid exhumation at 24 and 15 Ma at the northwest tip of the range (Cardona et al., 2011b), and (3) asymmetrical exhumation for the to the northern and western sides (Parra et al., 2016, Parra et al 2017, Piraquive et al., 2017).

Published bed rock thermochronometric data by Villagómez et al.(2011b) (Figure 4), include 22 apatite fission track (AFT) largely collected along two elevation profiles, one in the Sierra Nevada Province at the range's western margin (Fundación profile; 10 samples) and one at the Santa Marta Province in its northwestern corner (Kennedy Profile; 11 samples). AFT ages range from  $23.3 \pm 4.4$  to  $53.8 \pm 8.2$  Ma in the Fundación profile, and from  $16.0 \pm 2.5$  to  $41.0 \pm 9.6$  Ma in the Kennedy Profile (Figure 3). In both cases, exist a relative good age-elevation correlation.



**Figure 4.** Available thermochronological data in the Santa Marta Massif and the western foothills of the Perijá range.

Additional sampled sites are included: Paleocene granitoids to the northern margin (2 samples;  $22.3\pm 3.1$  Ma and  $27.6\pm 4.6$ Ma) and Jurassic granitoids and felsic volcanic rocks at its northeastern margin (3 samples;  $40.4\pm 5.7$  Ma to  $59.6\pm 10.4$  Ma).

In addition , 15 apatite and 14 zircon (U-Th)/He (AHe and ZHe, respectively ) single grains have been obtained from 8 samples along the Kennedy profile, with good within-sample reproducibility and a fair to good age elevation relationship (Cardona et al., 2011b) (Figure 3). Weighted average AHe ages range from  $7.6\pm 0.8$  to  $24.5\pm 7.0$  Ma and ZHe ages from  $20.6\pm 0.6$  to  $24.3\pm 0.5$  Ma.

Recently detrital AFT and ZFT data were published for Cenozoic strata from the Palomino margin to the north, and Aracataca margin to the west, assigned to Oligocene-early Miocene based on regional stratigraphic correlations (Piraquive et al., 2017). In the north, AFT data collected in one sample from the middle to upper Miocene rocks ( $15\pm 5$ Ma) reveal two AFT age populations of  $\sim 26$  Ma and  $\sim 53$ Ma, implying lag-times of  $\sim 15\pm 5$  Ma and  $40\pm 6$  Ma. ZFT detrital ages in 5 samples from the same strata collected along two stratigraphic sections yield age populations of 33-41 Ma,  $\sim 55$ Ma, 74-90 Ma, 108-132 Ma, and 156-170Ma and 254 Ma. From them, we interpreted that only the two youngest population may reflect reset ages related to the Cenozoic Andean cycle of exhumation. In the sedimentary sequence of the western margin (Aracataca), recently dated as early Miocene (Echeverri et al.,2016), were dated 2 AFT samples that yielded age peaks of 19-22Ma, 30Ma and 42-60Ma; and 3 ZFT samples with age peaks of 29Ma, 48-52-74Ma , 104-108 Ma and 167 Ma. The youngest cooling ages imply a shorter AFT lag-time of  $\sim 4$ -10Ma.

Farther to the east, in the western foothills of the Perijá range, AFT cooling ages of Jurassic-Cretaceous rocks completely annealed range between  $\sim 3$ -10Ma (Hernandez and Jaramillo et al.,2009).

## 5. Methods

### 5.1 Apatite fission tracks thermochronology

Apatite is a U-bearing common accessory mineral in geological materials and therefore has been widely used as U-Th/He (Farley, 2000) and fission-tracks (Laslett et al., 1987) dating targets. These low-temperature thermochronometers are useful to study the thermal history of upper portions of the crust that result from the exhumation of rocks toward the earth surface, a process promoted either by erosion (climatically or tectonically induced) or by normal faulting (England and Molnar, 1990; Stockli, 2005)

The fission track method exploits the crystalline damage generated by natural fission of the  $^{238}\text{U}$  in U-rich minerals. Such damage, called a fission track, is produced by spontaneous nuclear fission of the  $^{238}\text{U}$  nuclei into two particles ensuing an energetic displacement in opposite directions that is recorded into the crystal lattice. In this context,  $^{238}\text{U}$  constitute the radioactive parental element of the radio-chronometric system and the spontaneous fission tracks constitute its radiogenic daughter product (Price and Walker, 1963; Fleischer and Price, 1964; Fleischer et al., 1975).

Subsequently to the formation of spontaneous tracks, exposure of rocks to high temperatures reduces progressively the track length from the initial  $\sim 16\ \mu\text{m}$  for apatites, in a process called annealing. This process is mainly controlled by solid state diffusion and lead to the time and temperature dependent repairing of vacancies in the mineral crystalline lattice. Field observations of naturally annealed apatites from well samples (Gleadow and Duddy, 1981) allowed defining an interval of temperature between  $\sim 120\text{-}60^\circ\text{C}$  (Green et al., 1986) where the process of annealing mainly occurs, and which defined the so called apatite fission tracks Partial Annealing Zone (PAZ)

In addition to observations of naturally annealed apatites, laboratory track-annealing experiments under controlled time and temperature conditions (Green et al., 1986, Ketcham et al., 1999, Ketcham et al., 2007), have provided insights into the kinetics of fission track annealing and allow using track-length data to inverse model thermal histories

Besides temperature and time of heating/cooling (heating/cooling rate) (Reiners and Brandon, 2006; Green et al., 1989), empiric observations demonstrate that track annealing is also correlated

with apatite chemical composition and grain solubility. In particular, chlorine content and the solubility of the crystal in the etching solution, expressed as the diameter of the polygon formed by intersection of the fission track and the polished surface of the crystal, called Dpar (Donelick, 1993; Ketcham et al., 1999), have been identified as kinetic parameters and have been incorporated into the kinetic models (e.g., Ketcham et al., 2007). Apatites with larger Dpar and higher Cl content are in general more resistant to the annealing process (Donelick et al., 2005).

As is the case for all radiochronometric systems, fission-track analyses require the quantification of the parent ( $^{238}\text{U}$ ) and daughter (fission-tracks) products. Determination of the relative uranium concentration in apatite grains can be achieved either inducing fission of the  $^{235}\text{U}$  by thermal neutron activation (Tagami and O'Sullivan, 2005), or employing laser ablation-Inductively plasma mass spectrometry measurements (Hasebe et al., 2004, Donelick et al., 2005). Fission-track quantification requires exposure of fission-tracks in polished surfaces of apatite grains and a subsequent acid etching of the surface in order to reveal the tracks. Track density estimation is conducted in an optical microscope, usually at 1250X magnification.

For this study, we used the external detector method (EDM, Gleadow, 1981), which required for each sample an assembly of a mount of polished and etched grains coated by a U-free muscovite sheet. This assembly is exposed to a flux of thermal neutrons in controlled conditions to induce fission of the isotope  $^{235}\text{U}$ , producing tracks that will be recorded in the mica. Both spontaneous and induced fission track densities are obtained by counting in an optical microscope (Fleischer et al., 1975). The initial content of the parent isotope  $^{238}\text{U}$  is calculated employing the constant ratio between  $^{238}\text{U}/^{235}\text{U}$  and together with the spontaneous fission tracks constitute the isotopic ratio used to obtain a cooling age.

## **5.2 U-Th/He in apatite**

The U-Th/He method is based on the radioactive decay chain of the isotopes  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{147}\text{Sm}$  by  $\alpha$ -emission, that consist in the ejection from the nucleus of a pair of protons and neutrons that conform a helium nucleus. The accumulation of  $\alpha$ -particles occurs in apatite in trace quantities high enough to be reliably measured with modern mass spectroscopy, which enables its use as a low-temperature thermochronometer (Zeitler et al., 1987). For this system, the favorable thermal

conditions of helium accumulation correspond to temperatures below  $\sim 40 - 70^\circ\text{C}$  (Farley, 2002; Wolf et al., 1996). Such range of maximum temperatures has been called the Partial Retention Zone. Results of diffusion experiments in heavily radiation damaged apatites, such as those with very large U-content or that have accumulated lot of damage due to long residence at low temperatures, have revealed a higher temperature, in excess of  $120^\circ\text{C}$ , for helium retention. (Shuster et al., 2006; Flowers et al., 2009, Gautheron et al., 2009).

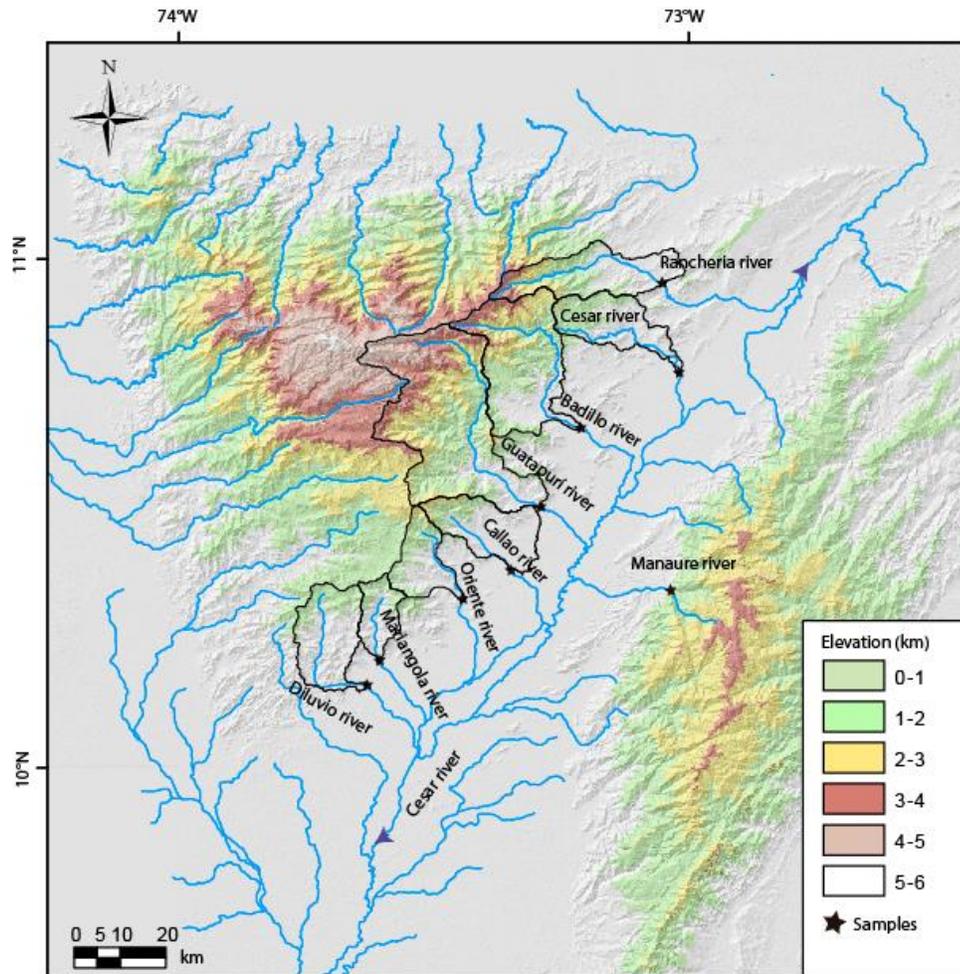
Alpha particles (i.e., He nuclei) are ejected from the nucleus of the parental element at a distance of  $\sim 20 \mu\text{m}$  and therefore can be ejected out from the crystal from parental nuclei located in the outer  $\sim 20 \mu\text{m}$  of the apatite crystal. Therefore, it is necessary to apply the alpha-ejection correction, called the Ft factor (Farley, 2002), which refers to the proportion of the crystal which retains He. This correction assumes a negligible external implantation of alpha particles and a uniform distribution of U-Th throughout the grain.

### 5.3 Analytical techniques

This study is based on the analysis of modern sediment samples collected in sand bars of rivers that drain the eastern side of the Sierra Nevada de Santa Marta. Fine-to-medium grained sand samples were collected in sand bars from the lower reaches of the Rancheria, Cesar, Badillo, Guatapurí, Callao, Mariangola and Diluvio rivers (Figure 5). The target mineral apatite were obtained by sieving, magnetic separation and heavy liquid standard techniques.

For fission tracks analysis, apatites were mounted in epoxy resin and then polished in order to obtain smooth surfaces. In order to reveal spontaneous tracks, apatite grains were etched with 5.5 mol.  $\text{HNO}_3$  at  $21^\circ\text{C}$  during 20 s. Each sample mount, as well as dosimeter CN1 and CN-5 glasses used to monitor neutron flux, were covered with mica sheets. Three of the samples were irradiated in the Oregon State University research reactor and the rest of them in the Nuclear and Energy Research Institute (IPEN) of the University of São Paulo exposing samples to a neutron fluence of  $3\text{E}15 \text{ n/cm}^2$ . Following sample irradiation, induced tracks were revealed in micas through etching with 40% HF at  $21^\circ\text{C}$  during 45 min. For each sample, additional aliquots of apatites were mounted and irradiated with  $^{252}\text{Cf}$  at the Department of Geosciences of the University of Texas at Austin in

order to increase the chance to find horizontally confined tracks for length measurements (Donelick and Miller, 1991).



**Figure 5.** Sampled sites. Delimited areas correspond to the studied catchments.

All samples were analyzed in an Olympus BX51 microscope in the Low-Temperature Thermochronometry Laboratory (LabTer) at the IEE-USP employing a 1250x magnification and dry objective, and with an attached electronic stage, a digitizer tablet and the software FT-Stage (Dumitru, 1993). Age determinations were performed through the zeta calibration method (Hurford and Green, 1983), with zeta values (CN-5 glass) of  $335.7 \pm 6.6$  obtained from Fish-canyon and Durango standar apatites.

For (U-Th)/He dating, hand picking of around 30 inclusion-free and unfractured apatite grains was performed at the LabTer IEE-USP under an Olympus SZX-16 a binocular microscope equipped with a rotating tablet, polarized light and a digital camera. Crystal dimensions necessary to model helium diffusion were recorded and then each grain was packed in a platinum tube. Subsequent analysis were carried out at Potsdam University and in the German research center for geoscience (GFZ). The tubes were heated twice using a diode laser for 5 min, to guaranty total Helium degassing. After helium extraction Pt tubes were dissolved and spiked with ~0.45 ng  $^{230}\text{Th}$  and 0.20 ng  $^{235}\text{U}$  with approximately 2mL of  $\text{HNO}_3$ , and U, Th, and Sm analyses were performed on a VG plasma Quad PQ2+inductively coupled plasma–mass spectrometry. Corrections for alpha ejection (Ft) close to the grain borders, were carried out assuming homogenous Ue distributions within the crystals.

## Conclusions

Detrital thermochronology allow establishing an episodic uplift of the Santa Marta Massif comprising the Cenozoic orogeny. A Paleocene-Eocene pulse related to the eastward tilting of a former continuous belt that included the Central Cordillera and Santa Marta massif, a Late Oligocene-Miocene related to the opening of the Lower Magdalena Basin , and the more recent pulse detected for eastern side during the Middle Miocene possibly related to a reactivation of the Santa Marta Bucaramanga fault. Thermokinematic modelling reproduce an asymmetric pattern of integrated exhumation rates since 65 Ma to present. From the modelling is suggested in northwestern corner exhumation rates of 0.26 -0.18 km/My similar to an exhumation rate derived from the geobarometry of the emplacement of the Santa Marta batholith ( ~0.3 km/My).. At the eastern side of the massif were obtained exhumation rates of 0.05-0.15 km/My that are close to the rates derived from the 1D analysis for samples with available AFT and AHe data (Ranchería, Badillo and Guatapurí). Correlations between the log-likelihood parameter for the predict ages and the velocities impose to the model suggest an inhomogeneous exhumation in the shallow crust above the 120° C isotherm. Whilst AFT system yield better fits with velocities below 2.0 km/My, the AHe require velocities 2 km /My up. Such pattern suggests and acceleration of the exhumation during the Miocene.

Further parameters as growing of topography and multiple time intervals for the tectonic scenario of the modelling would improve the fit between predicted and measured ages. However, parameters considered here provide a good baseline of the exhumation rates that have been present in the Santa Marta massif.

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